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Enhanced Resistive Reconnection: an Experiment to Demonstrate Scattering of $J_{||}$ by Non-Linear Lower Hybrid Waves

PI's

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Start Date

The project is to begin October 1, 2003 with a duration of 3 years.

Objectives

We are proposing a small laboratory plasma experiment to test whether an ensemble of powerfully excited lower hybrid waves can behave as a $J_{||}$-excited non-linear, large amplitude oscillation, fed by the free energy of force-free magnetic fields. Here $J_{||}$ is the current density parallel to the background magnetic field. The objective is to explain the very large enhanced resistivity, (up to ~ 10^{25} times classical) implied in astrophysical reconnection circumstances, as for example in giant radio lobes. The free energy of force-free fields, (low β: ratio of plasma pressure to magnetic field pressure), can only be accessed through the $J_{||}$ supporting the fields by creating an average $\langle E_{||} \rangle \cdot J_{||}$. We would like to observe whether an $\langle E_{||} \rangle >> \eta J_{||}$ (η the classical resistivity) is produced by the excitation of several large amplitude, nonlinear m=0 (cylindrical symmetry) lower hybrid waves, and furthermore whether a fraction of the free energy released by the waves can lead to amplification of the waves. We suspect that only an ensemble of large amplitude lower hybrid waves (ELALHWs) can fulfill such a requirement (with the possible exception of Buneman modes). We recognize that flux conversion by, for example the tearing mode, can prepare a reconnecting plasma for a hierarchy of plasma instabilities where this mode may be important [*Birn et al.*, 2001].

A small plasma experiment (4 cm diameter by 1 m long, weak field, ~100G, low density, n_e ~ 10^{15} m^{-3} and powerfully pumped at the lower hybrid frequency, ~10^7 Hz, with up to 10 kW power, and an axial current, $I_{||}$ ~ 10 amperes is required. The axial potential difference between out-of-phase nodes identifies the wave amplitude. The change in the plasma resistivity, measured by the resistive potential drop of $I_{||}$, identifies the sought-for enhanced nonlinear wave impedance. Any positive change in the wave amplitude due to the axial current may identify positive gain.

Background

The most luminous objects of the universe are quasars, which are generally recognized as being formed by the energy released in the formation of the super massive black holes, central to almost every galaxy. This energy is ejected from the accretion disk forming the black hole as powerful jets, emitting in the optical, x-ray, and gamma-ray spectrum that ultimately evolve into giant radio lobes: radio luminous regions of space whose dimensions are of the order of the galaxy spacings. These giant radio lobes are almost as luminous as the quasar itself in their respective part of the spectrum.

We emphasize these radio-emitting objects because they challenge our possible understanding of quasars more deeply than almost any other observation [*Kronberg et al.*, 2001; *Nishimura et al.*, 2003]. The origin of radio luminosity is universally agreed upon as being uniquely due to synchrotron radiation, that is relativistic electrons in a magnetic field. Thus, the total energy of a radio lobe must include both the magnetic energy as well as that of the relativistic synchrotron emitting electrons. Equipartition demands that the total energy is minimized when these separate components are equal. This total energy is truly awesome, as Burbidge pointed out in 1953, $\sim 10^{61}$ ergs. However, now with the knowledge of universal super massive black holes, ($\sim 10^{62}$ ergs) this total radio lobe energy becomes realistic, provided most of the free energy of black hole formation is converted into magnetic energy. Equally challenging is that half this magnetic energy must be used to accelerate highly relativistic, ($\gamma \sim 10^5$) electrons.

The requirements for this conversion process, a form of acceleration during reconnection, is the subject of this proposal. This is also the same problem, but in less extreme circumstances, inferred for the sudden giant, over-the-limb, x-ray flares on the sun, as well as "disruptions" in fusion tokamak experiments. Both magnetic configurations are cylindrically symmetric force free fields.

Reconnection

Reconnection is the general processes of reconfiguring the topology of magnetic fields and releasing any free energy of the reconfiguration into kinetic energy of particles (thermal or non-thermal). A major fraction of the theoretical and modeling effort of the Directed Research Active Galaxy project (LDRD funded), is directed towards understanding this problem. Cylindrically symmetric force free fields seek a lower energy state by reconnection, a Taylor state where $\nabla \times B = \lambda B$, where λ is a constant. In general, the process requires finite resistivity or collisionless tearing in order to enable the growth of the tearing mode instability. The "tearing" processes usually gives rise to current concentrations, which in turn lead to current carrier starvation and then current carrier runaway, leading to velocity distributions that are unstable to the Buneman instability. Finally, from this instability is obtained a highly enhanced resistivity. It is the difficulty in applying this scenario to the radio lobe and over-the-limb solar flares that has encouraged us to consider an alternate source of enhanced resistivity: one that does not rely on current starvation.

Plasma resistivity, as Spitzer has shown, depends upon the momentum exchange by scattering, leading to a net force between ions and electrons, i.e. scattering of the current carrying particles by coulomb forces. Using a classical resistivity, a plasma supported current on the scale of a radio lobe, $d \sim 30$ kpc = 10^{23} cm, at a temperature of 100 eV would allow the diffusion and energy conversion of the fields on a time scale of $d^2 / \eta \sim 10^{42}$ seconds, or 10^{25} times the Hubble time. Here $\eta \sim 10^5$ cm^2/s. Flux conversion by tearing mode reconnection leads to current concentration. The size of a single current channel necessary to give rise to diffusive dissipation of the magnetic energy in a radio lobe lifetime of 10^8 years becomes 10^{10} cm. A single filament carrying all the current on this small scale would be dramatically evident, and is excluded by observation. Many filaments of still smaller scale become a problem, because many filaments give less dissipation per filament. Current starvation in the intergalactic medium (IGM) is also difficult to achieve because the drift velocity necessary to carry the current, $I \sim d \cdot B = 10^{19}$ A by an IGM electron density of 10^{-5} cm^{-3} without filamentation becomes $v_{\mathrm{drift}} = 3 \times 10^{-4}$ cm/s or $3 \times 10^{-12}\ v_{\mathrm{thermal}}$.

Lower Hybrid Waves

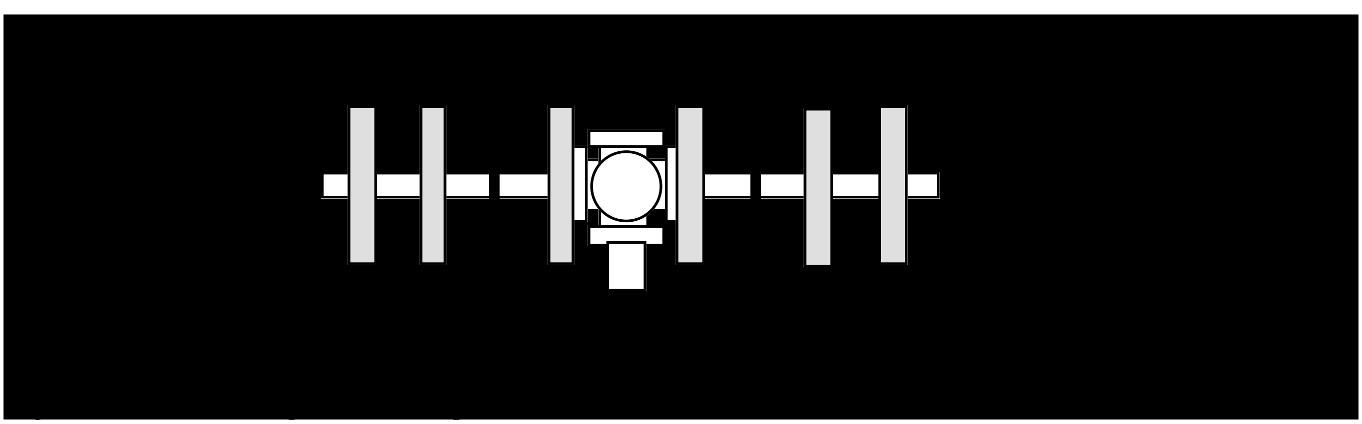
Lower hybrid waves can be understood as whistler waves with a finite $k_\perp$. In cylindrical symmetry, m=0, as in the proposed experiment, a plasma in an externally produced axial magnetic field is compressed and expanded locally in r by a <u>slow</u> oscillation of a boundary magnetic field. The resulting oscillation will propagate an Alfvén wave in either direction in z from the local region Δz. The electrons and ions will remain closely tied together following the compressed and expanded field lines on the assumption that the Larmor radii and Debye lengths are small compared to R, the radius of the plasma. As the ion Larmor radius is made large compared to R, charge separation electric fields are expected to still maintain the electrons and ions closely together. When now the oscillation frequency becomes high enough, near the lower hybrid frequency $(\omega_i\ \omega_e)^{1/2}$, the ions will oscillate radially a distance of the Debye length (small compared to the ion Larmor orbit), while the electrons will drift alternately azimuthally with $v_{\text{drift}} = E \times B$ in the charge separation electric field. The magnetic force on the electrons, eBv_{drift}/c of the electron drift velocity balances the radial inertial force, $m_i\ d^2r/dt^2$, of the ions. The oscillation becomes nonlinear or large amplitude when this distance of charge separation becomes of the order of the Debye length. This also describes a large amplitude $m=0$ helicon mode. We thus have an oscillation where the electrons are immobilized by a magnetic field and the ions are free to oscillate radially in the charge separation electric field. A charge neutralization current will flow when two axially separated regions are out of phase.

Approach

Experimental setup

To test the lower hybrid current generation scenario we propose a simple experiment. A sketch of the experimental hardware is depicted in Figure 1. The device consists of a central stainless steel 6-way cross vacuum chamber (ISO 160) and two pyrex tubes of 4 cm diameter at either end. A set of six magnetic field coils (50 cm diameter, 40 turns each) provides the axial background magnetic field. The lower hybrid waves will be launched by two m=0 antenna loops surrounding the pyrex tubes. At the extreme ends of the pyrex tubes are two conductors (coated cathode and anode) for driving current along the device axis. A small turbo pump and roughing pump maintain the vacuum in the 10^{-7} torr range. An extended range pirani gauge monitors the pressure over the regime of interest (10^{-7} – 1 torr).

For these studies, the lower hybrid wave excitation mechanism will also serve as the RF plasma ionization source through the helicon mode. Helicon waves (bounded whistler waves) lie on the fast branch of the cold plasma dispersion relation, propagating in the lower hybrid regime, $\omega_{ci} << \omega << \omega_{ce}$. They are right-hand circularly polarized electro-magnetic waves propagating along the magnetic field. Helicon sources were originally used in plasma processing [*Boswell et al.*, 1982; *Chen*, 1992; *Chen*, 1996], but have now found their way into laboratory research of both fusion [*Boswell*, 1984] and space plasmas [*Scime et al.*, 1997]. Extensive studies have been done characterizing their ionizing capabilities over a wide range of plasma parameters and background magnetic field strengths [*Chen et al.*, 1997; *Keiter et al.*, 1997]. Typically,



helicon sources produce high density ($>10^{19}$ m^{-3}), low temperature (~10 eV) plasmas with a cross-sectional area of 10-100 cm^2. The helicon dispersion relation relates the plasma density to the background magnetic field and source diameter. For a given B_0, excitation frequency ω, and wavenumber k fixed by the antenna length, this relation determines the density achievable in the plasma. A significant additional advantage is the only modest power is required to sustain the discharge.

Densities typically generated at low background magnetic field strengths (~100 gauss) are $\sim 10^{17}$ m^3 [*Chen et al.*, 1997]. For these fields the lower hybrid frequency is ~3.3 MHz in helium and 6.5 MHz in hydrogen. These frequencies are in the standard ham radio band. A simple calculation assuming the single loop turn antenna yields a maximum fluctuating magnetic field given by

$$B = \sqrt{\frac{\mu_0 P}{2\pi\omega r^3}}$$

where, P is the RF power and r is the antenna radius. This yields a field of ~ 10 gauss at 5 MHz excitation frequency for an 4 cm diameter antenna and 1 kW RF power, or ~10% magnetic field compression for a 100 gauss background field. This compression is sufficient to exite waves in the nonlinear regime.

Experimental Plan

The plan of experimental studies seeks to establish that lower hybrid waves can indeed behave as a self-excited non-linear large amplitude oscillation fed by the free energy of force-free magnetic fields. We will proceed in three phases over the duration of this three-year proposal. During the first phase we will construct the experiment and begin studies of coupled lower hybrid oscillations and the generation of $E_{||}$. During the second phase we will study the self-excitation mechanism through wave interaction with an axially driven current. In the third phase we will study nonlinear three wave interaction.

For our initial experiments we plan to use two m = 0 type antennas to launch axisymmetric waves. The antennas are separated by 1m. A simple pi matching network will be used, and the current to antennas will be adjusted so that they are π out phase with each other. In this setup we can test whether interacting lower hybrid waves can induce an average $E_{||}$. In this experiment, because the ion inertia, for large amplitude waves we expect significant charge separation perpendicular to the magnetic field at frequencies near ω_{lh}. The phasing of the antennas is expected to lead to current flow along the device between the two antennas to cancel this charge separation.

Triple tipped Langmuir probes will be the primary diagnostic. We can measure the background plasma parameters, T_e and n_e and also the local plasma potential. In this configuration RF compensation is not required. Using the plasma potential measured at multiple locations radially and along the chamber axis we will be able to infer the sloshing of the current between the antennas during the coupled wave interaction. We can also measure the current profile directly using an array for miniature rogowski coils, as developed at Princeton Plasma Physics Labs. Miniature b-dot coils will provide information about the fluctuating magnetic fields.

In a related set of experiment we will investigate the effect of an externally excited axial current on the wave interaction. Lanthanum hexaboride (LaB_6) coated cathodes can provide current densities of up to 100 A/cm^2, for than sufficient for our purposes. We intend to drive current up to ~10 A along the axis. This current should increase the wave amplitude, demonstrating the complementary component of the wave self-excitation mechanism. Lower hybrid wave excitation using an axial current has already been demonstrated in a different parameter regime [*Rosenberg and Gekelman*, 1998], which will provide a nice comparison to our results.

During the 3rd phase of the research we intend to investigate nonlinear three wave interaction with three separate excitation antennas. Our previous studies coupled with detailed theoretical modeling will guide these experiments. We plan experiments using both sources with different phase relationships and slightly differing frequencies to understand under what circumstances small amplitude waves can couple to generate $E_{\|}$.

Modeling and Computing

Theoretical modeling of large amplitude lower hybrid waves in regimes relevant to the proposed experiment requires a kinetic description of the plasma. We will employ a fully kinetic particle-in-cell (PIC) code developed at LANL to run on the massively parallel ASCI Q machine [*Daughton*, 2002]. This two-dimensional code solves the Vlasov-Maxwell system of equations using a well-known electromagnetic algorithm in which the fields are advanced using the scalar and vector potentials [*Morse and Nielson*, 1971]. To model the $m=0$ modes in the proposed experiment, the code will be modified to treat axisymmetric cylindrical geometry. We will employ a conducting boundary condition at the radial boundary and allow the possibility of a variety of boundary conditions in the axial direction. Although fully kinetic simulations are computationally expensive, the code has been demonstrated to scale very well on the ASCI Q machine up to 256 processors, which should allow us considerable freedom in choosing a range of plasma parameters to better understand and interpret the experimental results.

Resources and Existing Facilities

Los Alamos will provide the computing resources for the theoretical modeling of the experiment. The experiment leverages off the existing laboratory facilities at New Mexico Tech (NMT). Tech has the required power RF amplifies, DC magnet power supply, vacuum gauge and controller, and data acquisition hardware. The LANL directed funded research on Active Galaxies helps support at NMT a closely related experiment, an Alpha Omega Dynamo in liquid sodium in support of our understanding of the Magnetized Universe.

Statement of Work

The tasks to be performed under this project are stated in detail in the Approach section. Specifically, we will

1) Construct a device and measure the on-axis current generated but competing large amplitude lower hybrid oscillations.
2) Measure the excitation of lower hybrid modes due to an externally applied axial current
3) Undertake a program of computational modeling to couple theoretical predictions with experimental measurements.

Proposing Team

Dr. Watts has expertise in experimental plasma physics and will oversee the experimental component of this proposal. The PhD graduate student will carry out most of the primary experimental duties under the guidance of Dr. Watts. These include construction of the experiment, experimental data taking and analysis. Drs. Colgate and Daughton are experts in theoretical and computational plasma astrophysics. The computational modeling will be done largely while the student is resident at LANL, under the guidance of Drs. Colgate and Daughton during the summer. Because of the proximity of LANL to NMT, frequency site visits and exchanges are expected.

Significance

Identification of the acceleration mechanism of relativistic particles in astrophysics would help enormously toward understanding galactic scale dynamics. Should the expected result occur, namely the amplification of large-amplitude lower hybrid waves (ELALHWs) by the current $J_{\|}$, then we will have come close to solving the enigma of the mechanism by which rapid dissipation and conversion of magnetic free energy into accelerated particles occurs. No other mechanism for creating this extreme enhanced resistivity has been suggested, where the drift velocity of the current carrying electrons is many orders of magnitude less than the thermal velocity of the plasma. Our approach, coupling experiment and modeling will provide the surest test of this mechanism.

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